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THE ARC IN HIGH VACUA.

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CONTENTS.

I. Introduction.

II. General Statements.

III. Object of Investigation.

IV. Apparatus.

V. Experiments on Cathode Rays.

VI. Action of a Magnetic Field.

VII. Current Measurements.

VIII. Study of Spectrum.

IX. Summary.

X. Biographical Sketch.

The Arc in High Vacua.

Introduction.

If a discharge tube is made with the electrodes placed opposite and extending very close to each other, e.g.1 mm apart, one may observe the following phenomena as the pressure is gradually reduced. With pressure of the order of 1 mm of mercury, the current passes in the form of the ordinary purple glow. As the pressure is lowered, the luminosity of the gas decreases and there is a noted increase in the potential difference necessary to cause the discharge to pass. This last fact is strikingly illustrated in the classical experiment of Hittorf*. Professor Thomson in his theory of the discharge through gases, has shown that the potential difference necessary to produce the discharge in a vacuum tube must become very much greater if the distance between the electrodes is made less than the length of the negative dark space at the existing pressure. If the potential difference between the electrodes is still further increased by put-

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* Wied. Annal. 21, p 96, 1884.

ting in a spark gap in series with the tube in the circuit leading to the electrical machine, cathode rays are given off strongly even at a pressure of 1 mm. When a pressure of a few thousandths of a mm. is reached, if the external spark gap is increased to 2 or 2.5 cms. the profuse cathode discharge, and the attendant phosphorescence over the surrounding glass walls vanishes, and the current passes in the form of a brilliant spark or arc between the electrodes.

Soon after the discovery of the Roentgen rays, Professor Rowland* in the course of some experiments on the source of the radiation noticed in one of his tubes having aluminum electrodes about 1 mm. apart, that when the pressure was extremely low, the discharge passed as a "spark or arc" between the electrodes. He observed that the spot of light on the anode was the seat of very strong Roentgen radiation. Professor R. W.Wood ** working independently, published about this time a paper on "A New Form of Cathode Discharge and the Production of X-rays, together with some Notes on Diffraction" in which he noted many of the properties of the discharge and mentioned some points deserving further study.

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* Physical Papers, p. 574.
** Physical Review 5, p. 1, 1897.

General Statements.

Before taking up in order the several lines along which this investigation was directed, I shall give a brief description of the arc as I have produced it. Then I shall indicate the view which I was led to take concerning the nature of the discharge. Thus will be made apparent the points chosen for special study, the results of which have substantiated the view adopted. There will also appear the grounds on which I have chosen to speak of the discharge as an arc, although it is of course intermittent.

The electrode which I have found to give the most intense light are platinum beads about 1.5 mms. in diameter, easily made by passing the end of a platinum wire in the oxyhydrogen flame. If the vacuum is good, say a few thousandths of a mm and the beads are placed 2 or 3 mms apart, the cathode rays go off in every direction from the negative electrode, but principally in the horizontal plane normal to the cathode wire and containing the negative bead . If now a spark gap of 2 or 2.5 cms. is introduced in the circuit leading to the machine and the

electrodes are brought nearer together, when they are within about 1 mm of each other, the phosphorescence on the walls of the vessel vanishes and there appears the brilliant light on the anode bead.

But while under these circumstances there was no phosphorescence on the walls of the outer tube, there was a bright glow on the small capillary tube into which the anode wire was sealed (see fig. 3), extending several centimeters beyond the seal. This phosphorescence on the anode tube did not appear at relatively high pressures, but only when the pressure and distance between the electrodes were such as to cause a very high potential difference, i. e. only when there was a strong electric field around the electrodes. It was also observed that when this glow first became distinct on the anode tube, there was often a faint glow on the cathode tube also, but this did not persist at very low pressures or when a wide external spark gap was put in. A tube having platinum wire electrodes sealed into bulbs joined by a capillary, showed that when the potential difference between the electrodes was not too high, cathode rays were given off with very rapid alternations by each wire, principally by the normal cathode,

and less by the electrode joined to positive pole of the machine. The discharge from the machine was therefore under these conditions oscillatory, or was shown also by a telephone placed in the circuit. Thus the occasional appearance on the cathode tube of the phosphorescent glow, such as persisted on the anode tube, but no where else when the potential difference between the electrodes became very high, was due to its being temporarily an anode. The persistent phosphorescence on the anode tube is due, I think, to two causes. Some cathode rays shot off from the cathode towards the anode do not strike the bead but go just by its edge and moving parallel and very close to the anode wire and tube, are drawn in by the very strong field about the tube and so strike against it, causing the phosphorescence and a feeble emission of Roentgen rays. Moreover there is a small quantity of gas present in the vessel, and gas is being given off continually by the beads particularly by the anode which suffers disintegration, so that the pressure about the electrodes is probably appreciably higher than the average pressure in the system which is registered by the gauge. This gas about the electrodes and specially in the region around the positive wire and tube being ionized by the cathode rays which go past the

positive bead, we may expect that the electrons or negative particles thus set free will be drawn in toward the anode, and in moving through the high potential gradient near the anode tube acquire sufficient energy to cause phosphorescence. Such an accelerating action of the positive electrode on the cathode rays is illustrated in many Roentgen ray tubes where it is found that the emission by the anticathode is markedly increased if this is made the anode or is joined with the anode. In fact instances may be cited in which the anticathode gave no evidence of even a feeble Roentgen radiation unoless it was made anode, in which case it became a strong source. If the above explanation of the glow on the anode tube is correct, we should expect that any screen or obstacle, placed in close to any part of the anode wire or tube so as to obstruct a section of those cathode rays which pass by the anode beads, would produce at most only a shading in the glow on the tube, and not a complete shielding, for there would still remain the effect due to the electrons set free in the surrounding gas by the stray cathode particles.

After the arc has commenced to pass steadily the distance between the electrodes may be increased to 1.5 mms. provided the vacuum is maintained by pumping (for the evolution of gas by the electrodes is considerable). Under these circumstances which are the most favorable for observing the discharge, the source of light has not the form of a continuous line reaching from one bead to the other, as is the case with the ordinary spark, but rather looks like a crescent on the outer or near surface of the anode. The accompanying drawing will make my meaning plain. This brilliant light is usually surrounded by a sort of halo or corona, the color of which depends on the metal of the anode. This halo was most marked with a magnesium anode, and was of a yellowish green

fig. I

color. If the discharge runs for some time, the end of the anode is markedly disintegrated. Red hot particles are shot off from the end of the anode in every direction. This effect was most striking in the case of a titanium anode, when the luminous particles were shot off in great numbers and often suffered several reflections from the walls of the vessel while still glowing. This disintegration of the anode is of course more marked for the volatile metals. There is also a deposit on the end of the cathode and the amount of this deposit is apparently proportional to the loss of the anode. Two specially well formed deposits and craters were noticed with a platinum cathode and magnesium and iron respectively as anode. I give sectional view of the anode and cathode before the discharge

fig II

and after it had run for about two hours. If the vacuum was about .001 mm and the external spark gap was closed so that the discharge became less intermittent, the anode bead was intensely heated, the small platinum bead could thus be raised to a white heat in a minute or less. This heating of the anode is of course only an example of the well known action of cathode rays on any obstacle against which they strike. If the discharge is intermittent, there is time between the showers for the heat to pass off by radiation and conduction along the wire. Again if the pressure is not extremely low, the potential gradient is not great enough for the cathode particles to be given sufficient energy to cause visible heating by impact. If the anode, instead of being a bead on a small wire was a small bar of metal 1.5 mms. in diameter, no visible heating effect could be produced, conduction in this case being too rapid.

Having observed that the anode wastes away as in the ordinary arc, that the light belongs to the anode rather than to the two electrodes equally, that it is much more intense than the ordinary spark in air between the same electrodes with the same source of current, that the anode

is (under certain conditions) visibly heated, I have chosen to designate the discharge by the word arc, not meaning that I consider it similar to a uniform steady arc, but rather that it is in these respects analogous to the arc, and, when the anode is markedly heated, possesses the essential characteristic of the arc. The fact that the light is emitted by the bombarded anode and that the luminosity as well as the heating of the anode seems to be due to the violent impact of the cathode particles makes it plain that the discharge cannot be strictly an arc or a spark, for no such conditions exist in either as they are commonly produced. The phenomena might seem to approximate more nearly to a possible state of things in the chromosphere where we may think of the matter as suffering severe impacts of the small parts against each other due to the falling in, under the sun's attraction, of material from the outer portions. Hence it was that I have studied the spectra of such substances as show strong chromospheric lines. Moreover, from the experiments of Hartmann* and others, it appears that the conditions for the existence

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* Astrophys. Jour. 17, p. 270, 1903.

of the so-called characteristic spark lines are fully met in this case, so that beforehand, we would expect to find these, whether there are present also characteristic arc lines or not.

Object of Investigation.

In the study of this discharge the points which seemed to merit special investigation were:

What becomes of the cathode rays when the profuse phosphorescence on the walls of the tube vanishes and the brilliant little arc appears?

What is the action of a magnetic field on the arc?

Is there any change in the current when the above mentioned change in the discharge takes place?

What is the nature of the spectrum of the light emitted, does it correspond in general to the characteristic spark or arc spectrum, is the character of the lines at all similar to the corresponding chromospheric lines?

Apparatus.

The vacuum was produced with a Geissler-Toepler mercury pump and the pressures were read with a McLeod gauge. The source of current was always a six plate Toepler-Holtz

electrical machine. This was used rather than a coil since such a machine gives a practically constant potential and unidirectional current. If working under favorable weather conditions, the current from the machine was about .15 milampere on closed circuit and .1 milampere with an external spark gap of 2.5 centimeters in series with the tube. These readings were made on a Roentgen Ammeter, kindly furnished by the Roentgen Mfg. Co. of Philadelphia. It was in every case necessary to have one of the electrodes movable, hence the discharge apparatus was always mounted on a glass tube about 85 cms. long dipping into a mercury basin. The lower electrode was sealed into a glass tube bent into the form of a U, one arm extending up the long glass tube in which the mercury formed a barometer column, the other being held in a clamp which was movable by a slow motion screw. The particular form of tube and other apparatus depended on the experiment in hand and will be described in connection therewith.

Experiments on Cathode Rays.

The vacuum apparatus used in all experiments in this connection was a small bell jar, 8 centimeters in diameter and 20 centimeters high, fastened to a ground aluminium plate with stopcock grease (prepared according

to the formula of Travers, "Study of Gases" p. 24 - 1 part vaseline, 1/8 part paraffin, 2 parts rubber). The lower electrode was always connected to earth. The platinum wires p and q, on which were fused the electrode beads, were sealed into capillary tubes, as thin walled tubing was often punctured by the discharge which seemed to prefer a path of 10 or 15 centimeters to the very short one between the beads. The tube carrying the electrode p was sealed into the mouth of the jar J with Khotinsky wax, and the aluminum plate A was similarly fastened on to the barometer tube,H.

fig III

Through H there passes, alongside the electrode tube, a glass rod R bent into a U at the bottom and at the top into a shape indicated in the figure, so that any kind of phosphorescent screen or obstacle could be mounted on this rod by being fastened on to a small piece of glass tubing which fitted rather snugly over the end of the rod. This cap could be made secure and rigid by a little wax warmed and put on the end of the rod as the cap was pushed down over it. The rod R is capable of a rather wide vertical motion, so that any part of any mounted screen could be brought opposite either of the electrodes p and q. A limited freedom of rotation of R about itself as axis made it possible to bring the screen up to the electrodes or to hold it quite out of the line of the discharge.

Now the very intense emission of Roentgen rays by the end of the anode very near to the cathode in a highly exhausted tube, as has been already alluded to, might seem to indicate a sort of focusing, so to speak, of the cathode rays on the anode surface just next to it. Moreover some Roentgen ray graphs taken by the writer with a pin hole camera seem to indicate that the surfaces most

vigorously bombarded by the cathode rays during the arc discharge are the opposite surface of the anode, the wire, except just above the bead, and the more or less blunt end of the glass tube into which the anode wire is sealed. The accompanying figure shows a plate obtained with a two hour exposure at a distance of about 10 cms. from the source. It may be remarked that there is no impression of the cathode, so that there seems to be no Roentgen radiation at the starting point of the cathode particles. A distinct impression was made by the lower surface of the anode in three minutes.

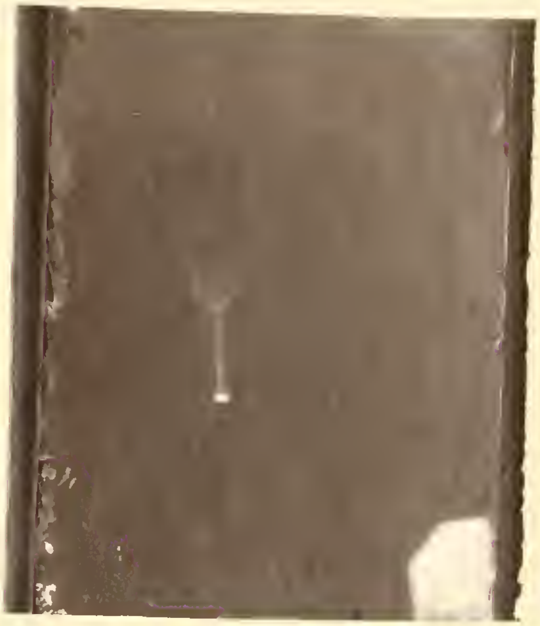

fig. IV

Hence it was thought probable that after the arc was formed, the distribution of the cathode rays was such as indicated in the drawing, i. e. the principal part of the discharge passes across directly from one electrode to the other, and the few cathode particles , shot out

at a small angle with the vertical and going past the anode bead, are deflected by the electric field which is very strong on account of the extremely low pressure and the nearness of the electrodes. These are thus drawn in towards the anode and so strike against the anode wire or the glass tube farther on. To test the views which I have indicated concerning the distribution of the cathode rays and the cause of the persistent glow on the anode tube the following experiments were made.

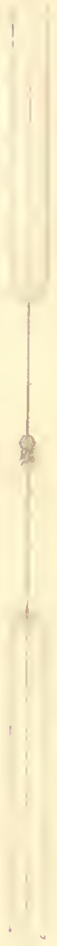

fig V

A small piece of copper foil about 5 mms. square, and coated over with ~~burnt~~ artificial ruby dust, which phosphoresces with a bright red color under the cathode rays, was mounted on

the rod R (fig. 3) with its plane vertical and perpendicular to a radius of the jar. By means of the rod the screen could be moved in a vertical or horizontal plane. Before the arc formed, if the screen was opposite the cathode bead or any part of that wire, there was a bright glow on the side of the screen next to the electrode and a weaker glow on the opposite side, the latter being evidently due to the diffuse cathode radiation from the walls of the jar. After the arc was formed there was no glow on the screen until it was moved up to or above the level of the upper bead which was anode. In such a position, however, there was now a glow on the outside of the screen, (though there was no radiation from the walls of the vessel) and none on the inside next to the electrodes. If the screen was moved up very close to the glass tube carrying the anode, there was a weakening of the phosphorescent glow on this tube, but not a complete shadow. A very strong phosphorescence was seen on the edge of the screen next to the cathode when the screen was so placed that its lower edge was opposite to or above the anode bead and was close in to the axis of the discharge. The fact that during the arc discharge, there was, for the above

mentioned position of the screen a glow only on the far side, shows that the cathode particles in the region are moving with appreciable velocity only toward the anode. This glow is thus due principally to the electrons generated in the region and drawn toward the anode by the electric field. The much stronger glow on the edge of the screen next to the cathode shows that besides these secondary rays, there are some which come directly from the cathode against this edge.

Such a screen as was described above was then mounted with its plane horizontal. Before the arc passed, if the screen was on the cathode side of the gap there was a glow on the surface facing the gap. But if the arc was formed there was no phosphorescence on the screen for such a position, but if it was moved opposite the anode wire or bead, and brought in very close to the wire, the glow appeared on the side facing the cathode; and this glow was much more intense on the parts of the screen nearest to the electrode wire. This was more marked if the screen was placed near the anode wire just beyond the bead. This screen, as the one above referred to, failed to cast any distinct or sharp shadow on the anode tube which as I have

said phosphoresced brightly for several centimeters beyond the seal of the platinum wire. This experiment also tends to confirm the opinion that some particles leave the cathode in a direction slightly inclined to the vertical and pass around the anode bead, but that most of them are confined to a region very close to the anode.

I then made a bead about 2 mms. in diameter on the end of a small wire, coated it with ruby dust and mounted it as the screens had been. With this it was possible to observe a distinct shading in the glow on the anode tube just opposite or rather a little beyond the bead when this was brought very close up to the anode tube or against it. There was not in this case, however, a complete screening of the tube from the bombardment of the cathode rays. Moreover the surface of the bead next to the cathode glowed slightly while there was practically no glow on the far side. It was readily seen with this bead also that the glow was much more intense if the bead was brought in near the axis of the discharge than if it was a few mms. off from the anode wire. This case admits of the same explanation as was offered at the end of the preceding paragraph.

Then in order to avoid as far as possible any disturbance of the electric field or other spurious effects due to the introduction of metallic screens into the vacuum space, some experiments were made with mica screens covered with phosphorescent powder and also with newly drawn fine wires of soft sodium glass, which seemed in some ways more satisfactory than the screens coated with powder, and were amply sensitive for rays moving with such high velocities as those I have dealt with.

First, a mica disc having a small hole in its centre and of such diameter that it would just slide easily in the jar, was covered with the phosphorescent powder and fastened to a glass frame which was mounted on the rod R. Let us suppose that the disc is in some position below the level of the arc gap and that the upper electrode is cathode. If the beads were brought near together and a spark gap opened in the external circuit so that the discharge changed from the profuse cathode glow into the arc, there was not any gradual change on the phosphorescent disc; it was not possible to obtain by raising or lowering the disc any varying sections of a cone of rays coming together toward the anode wire or tube; but this was plain, viz.; when the arc was passing

steadily, there was on the screen just around the opening in its centre an intense glow when the disc was in a plane just below the level of the anode bead. This clearly showed that all around outside the arc, cathode particles are moving in a more or less vertical direction, that not all of them have been gathered into the space between the opposite faces of the platinum beads, but that this is the tendency for before the arc formed there was no phosphorescence on this part of the disc; in fact none on any part of the disc till the arc was near the point of forming, the rays going off principally in a horizontal plane.

Now if there is no arc and the lower electrode is the cathode, the screen shows in different positions sections of what seems to be a hollow cone of cathode rays shot from the wire and lower part of the cathode bead, as indicated in the drawing. But if

fig VI

the conditions be changed so that the arc is about to form, this cone apparently spreads out or becomes more convex and when the arc appears, there is now no glow at all on the screen.

It then suggested itself to set up obstacles on the screen to see whether there could be formed such circumstances that the particles would be moving in a direction very nearly parallel to the face of the disc, so that a short obstacle would cast a rather long shadow. No affirmative results were obtained from this. If the rays sent out by the cathode, which was the lower bead, at first principally at a dipping angle, were, as the spark gap was widened and the field thus made stronger between the beads, at all deflected upward or caused to travel in even slightly curved paths, the effect was not noticeable. Here however we are looking for a deflection of the particles in a portion of the tube relatively far from the anode and so outside of the high-potential-gradient region just around this electrode.

From the appearance of the phosphorescence on a vertical glass wire mounted on the screen so as to examine a section of the so-called hollow cone alluded to above, it

it was thought that something might be learned as to the path of the rays when the arc was just about to form if there were set up on the disc several glass wires at different distances from the electrodes and if on these wires little knots were made so that the shadows of these would characterize the different vertical sections of the glass wires. The arrangement was as shown in the figure. If the electrodes were at a distance of 2.5 or 3 mms. apart so that the arc did not form the cathode rays came off principally from the part of the cathode wire marked p. As the spark gap was made wider and the electrodes brought nearer together, besides the rays going off in the direction pa there appeared

fig VII

strong rays along pb and with a wide external spark gap, say 4 cms. and a distance between the electrodes of 1.5 or 2 mms., still too great for the arc to form at the then existing pressure in the apparatus, the phosphorescence became exceedingly bright on the upper part of the tube and the shadows of the knots on the glass wires indicated that the rays were now coming off strongly in the direction pc, perhaps not from p but principally from the negative bead. These experiments show that as the proper conditions for the arc are approximated, the cathode rays come off successively from different portions of the surface of the electrode; e.g. with a short spark gap and the electrodes relatively far apart, the rays come from a point on the wire 3 or 4 mms. from the bead (unless the pressure is of the order of .001 mm.), if the spark gap is widened the rays come more from the terminal portions of the cathode, etc. Still another experiment was made to find out more about the paths of the rays just as the arc formed. A series of glass wires nearly 1 mm in diameter and placed about this distance apart were set on a glass frame and mounted so that the plane of the glass wires almost con-

tained the electrodes. On one of these glass wires a little piece of glass was stuck so as to project out normally to the plane of the glass wires. Now as the rays were moving at a small angle to the plane of the wires, this little obstacle should cast a rather long shadow along the direction of the rays exciting the phosphorescence. This shadow seemed in every case in which it was distinct to be straight, often there were two shadows, indicating that there were two points on the cathode that were emitting specially. When the spark gap was made wide enough to have the arc pass at all, the shadows ceased to be sharp and then gave no clue as to the path of the rays. This lack of sharpness was, I think, due to the diffuse cathode radiation from the surfaces bombarded by the direct rays, and to avoid this seemed impracticable, if not impossible. If it may not be claimed that these experiments are conclusive, they at least render very probable the view suggested as to the paths of the rays when the arc is passing and they indicate that the change from the profuse cathode discharge to the arc is an abrupt rather than a gradual one.

I then determined to look more specially for the source of the persistent phosphorescence on the anode tube near to and just above the seal of the platinum wire into the glass. A small glass wire, about 1.5 mms. in diameter was bent into a ring large enough to go over the anode tube and leave a space of at least 1 mm. all around. This was mounted on the rod R, and as the arc passed, was moved into various positions along the phosphorescent portion of the anode tube. Sometimes there seemed to be a faint shadow, but the cases were irregular and uncertain. Two little glass wires, about 3 mms. long stuck on to the anode tube radially, also failed to cast any distinct shadow along the tube. Bits of platinum wire gave similar results. The phosphorescence along the tube at points 2 or 3 cms. from the end was then not caused principally by the glancing impact of rays shot our from the cathode and moving in paths only slightly inclined to the axis of the discharge.

Next a sort of glass funnel was made with a hole just a little larger than the beads on the platinum electrodes. (The dotted portion of the figure on next page indicates a glass tube, to be spoken of later.) As the

figure shows, this funnel could be moved vertically throughout the length of the exposed platinum wires. By this means the rays going off from the cathode in a horizontal or slightly inclined direction were of course stopped and for such a position as is indicated in the figure, the upper electrode being cathode, no direct rays could pass into the region below the funnel close around the anode. However there was no position in which the glass funnel could be placed so as to stop the glow on the lower tube, the upper bead being cathode or on the upper tube if the lower electrode was the negative one; this was true when the arc passed as well as when it did not. This funnel showed, however, as did the phosphorescent disc above mentioned, that when the arc was passing or was

fig. VIII

on the point of passing i.e. was irregular, the strongest cathode rays passed along or in the general direction of the vertical and not in every direction off from the cathode ; for the inner portion of the funnel close to the anode was very much more phosphorescent than the outer parts.

Finally I concluded to join a piece of glass tubing to the neck of the funnel as indicated by the dotted lines in the preceding figure. If then the lower electrode was anode and the funned and tube was lowered till the neck of the funnel was against the tube where the anode wire was sealed in, there could be no direct passage of cathode particles down somewhat tangentially beside the anode tube, being finally drawn in against it; nor could the electrode tube be struck by any secondary cathode rays except such as might in some way be generated inside the shielding tube. We should then expect no glow at all on the anode tube on the portion inside the other one, or at most a very faint glow. It was found that the glow was distinctly weakened, but it was still considerable. The only explanation which I can offer of this is that the glass surfaces above which were bombarded by the direct cathode particles emitted into the space inside the larger

tube some ionizing radiation. Since this space was very limited the number of ions generated and so the number striking against the anode tube was smaller than if the tube had been removed, and so there was less intense phosphorescence than on portions of the anode tube that were not thus enclosed, e.g. below the outer tube.

Action of a Magnetic Field.

In studying the action of a magnetic field on the discharge the vacuum apparatus was a glas tube about 3 cms. in diameter having a T tube sealed into one side just opposite the electrodes and covered at its end with a glass plate sealed on with wax. In the first experiments to be described this side tube was normal to the plane of the axis of the magnet and the line of the discharge, and was 5 or 6 cms. long so that the glass plate would not blacken so rapidly with the platinum deposit, for the arc was observed through this side tube. The arrangement is shown in the drawing on the following page except that the side tube is here a very short one along the axis of the magnet, which was a later arrangement. N and S are the conical pole pieces of the electromagnet; these

fig. IX

are bored through the centre, so that, when desired the arc can be viewed by looking along the axis AB of the magnet. A variable resistance in series with the exciting coils enabled the strength of the field to be altered at will. With low presures, say 6 or 7 thousandths of a mm., if the external spark gap was adjusted and the electrodes so placed that the arc was just on the point of forming, i. e. passed irregularly, the effect of the magnetic field was to cause the arc to pass regularly or steadily; the field seemed then to aid the formation of the arc discharge. Again the magnetic field often caused the anode bead to become visibly heated. Both of these actions may arise from the fact that a magnetic field in general

hinders the discharge*. Here then its effect is to cause an increase in the potential difference between the electrodes and is thus analogous to a lowering of the pressure.

As evidence of the fact that cathode rays have a very much higher velocity when the magnetic field is on, the following phenomenon may be mentioned. If the arc is not passing, but we have the phosphorescent glow over the tube, the magnetic field twists into spirals, the paths of all particles except such as are moving parallel to the field, and these therefore form on the tube a sort of image of the cathode. There thus remain two bright phosphorescent spots on either side of the tube, and the intensity of the glow is much increased in these images, as I call them. On cleaning the tube with Aqua Regia, it was found that in these places the glass appeared etched. The drawing will indicate the outline and relative intensity of the etching.

fig. X

It seems worth mentioning that this

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* Thomson, "Conduc. through Gases." p. 474.

violent cathode discharge exerted some sort of deteriorating action on the walls of the tube around the discharge. For after a tube had been used for some days, it was found to crack very easily if put in the flame for any reason, and it was easy to break up the fragments of such a tube with one's fingers. I have never seen it stated that the glass of cathode tubes becomes specially fragile and have no explanation to offer, but simply mention the fact.

As to a deviation along the normal to the plane of the electric and magnetic force of the spot of light which marks the point of impact of the cathode particles , it need only be said that with such magnetic field strengths as I could obtain, calculation showed that the possible deflection of the rays was less than could be observed, specially since the arc was not stationery, but wandered about over the anode slightly according as one part or another of the cathode was specially active.

It remains to be said that the magnetic field did not noticeably alter the distribution of the phosphorescent glow on the anode tube, though there was a slight weakening of the effect.

Current Measurements.

Before I had the opportunity of using the Roentgen ammeter, I had made some readings with a small gas voltameter

in order to see whether there was any appreciable variation of the current as the nature of the discharge changed. However the current from the machine is very small and varies greatly with the weather conditions, so that I was not able to get any results which justified supposing that there was any material change in the current.

Measurements with the Roentgen ammeter did not show any change of current whether the discharge passed as the arc or whether there was the brilliant cathode glow over the tube, nor did the magnetic field have any readable effect. It is to be noted, however, that even a relatively large change in the resistance of the tube would make only a negligible change in the resistance of the whole circuit including the machine itself, and that we do not have at hand a large source of current. Hence no large current changes should be expected for any of the variations which we have made in the conditions or nature of the discharge.

Study of Spectrum.

The spectrum of the discharge was produced with a Rowland concave grating of 60 cm. radius. It was desirable to study specially the violet end of the spectrum as most of the substances examined have the strongest lines in this

region. Hence I used always a tube having a quartz window. The arrangement of the tube, slit, etc. is shown in the diagram. No lens was used as the arrangement would have required a specially ground one of quartz, and very little would have been gained by it any way

fig. XI

The time of exposure necessary was about one or one and a quarter hours. The films used were Eastman Kodoid, orthochromatic. The form of the electrodes was for one a platinum bead and for the other a small bar of the substance about 1.55 mm. diameter, fastened in the end of a brass wire. This wire, about 3 cm. long and having a screw socket joint in the middle, was fastened rigidly to a heavy platinum wire sealed into the upper end of the U tube. To change the electrode it was necessary only to lift off the bulb above the ground joint, unscrew the little brass end and replace it by a similar one containing a different substance. (For the calcium spectrum I used ordinary lime poked into a bored-out

brass wire.

The first substances tried were Mg. and Pt. as anode and cathode respectively. There seemed to be no trace of Pt. lines on the plate. It may be recalled here that I have said before that the light seemed to belong to the anode rather than to both electrodes; so I thought it worth while to test this point spectroscopically with two such metals as Mg. and Pt., the one very easily volatilized and the other quite the opposite. I therefore carefully cleaned the Pt. bead with acid and reduced the pressure to a few thousandths of a mm. If now the discharge was started with the Pt. as anode, an exposure of as much as two hours failed to show any sign of the Mg. lines. Of course it was not possible to get the spectrum of the other electrode only by simply reversing the current between exposures, on account of the previous deposit from the anode on the cathode. Nor was it possible to reduce the pressure gradually and determine by eye observations at what pressure the anode only was active, for sufficient Mg. got on the Pt. anode to show in the spectrum even after the pressure was so low that the Mg. cathode itself had ceased to play any part. In going from very low to higher pressures, the steps could not be made gradually and so all that I can say is that so long as the pres-

sure was low enough to cause the discharge to have the form of the little crescent of light on the anode, only the lines characteristic of the anode could be seen.

fig. XII. pres. .002 mm.

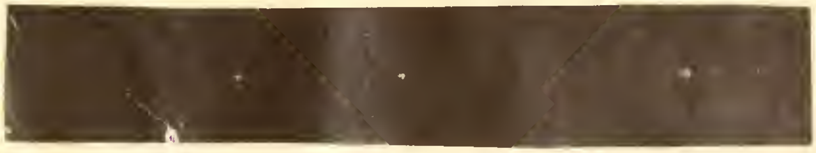

fig. XIII pres. .006 mm.

Fig. XII shows the result of a two hour exposure through glass with a Pt. anode and Mg. cathode.

Fig. XIII is for a Pt. cathode and Mg. anode.

Having shown that the spectrum was characteristic of the anode only, if the discharge passed in the form which I have designated on the arc, I obtained the spectra of Mg., Cu., Cr., Mn., Ti., and Fe. respectively by making anodes of these substances, the same Pt. cathode serving throughout the series. Only the stronger lines made an impression on the plates in the time given an exposure; these, however, were amply sufficient for purposes of comparison such as I had in mind. The general character of the spectrum does not correspond to that of the arc or spark. (I could not take the ordinary arc or spark spectra on the same film with the

spectrum of this anode light and the intensities for these as given in the tables below are from Exner and Haschek). Nearly all of the strong spark lines appear and the spectrum is very much more like the spark than the arc. But the relative intensity is by no means the same for all the lines. Nor does there seem to be any close analogy between the intensities in this case and those of the atmosphere.

There is observed here, however, an effect analogous to that brought out by Petaval and Hutton* viz., certain lines have in this vacuum arc an intensity which is not at all in the same proportion to that of neighboring lines as in the ordinary arc or spark. It is doubtful if in this case the sole cause is diminution of pressure, but probably it is due both to the low pressure and to the fact that the luminosity is here excited under conditions materially different from those existing in the arc or spark in air.

I give below a list of the stronger lines showing on my plates, with their relative intensities in the ordinary arc and spark, chromosphere, and the arc as I have produced it in the vacuum tube. I shall designate these respectively by A, S, C, and Av.

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* Phil. Mag. 6 p. 569, 1903.

Magnesium.	Intensity			
W. L.	A.	S.	C.	Av.
2777	20	6		2
2778	20	5		1
2780	30	10		3
2782	20	5		1
2783	20	6		1
2791	5	100		12
2796	200	500		10
2798	2	100		8
2803	100	500		8
2852	500	100		8
2929	2	200		6
2937	3	200		8
3829	30	200	5	5
3832	50	300	7	9
3838	100	500	10	15
4481	0	50	1	20
5073				?
5168			2	0
5173			4	1
5184			5	2

Calcium.

W. L.	Intensity			
	A.	S.	C.	Av.
3159	10	50		1
3179	15	50		2
3706	10	50	10	3
3737	20	50	15	5
3934	500	1000	75	25
3969	300	500	60	20
4227	1000	100	8	5
4283	50	20	1	0
4289	50	20	5	0
4299	30	20	1	00
4303	100	50	2	3
4308	30	20	5	0+
4318	50	30	1	1+
4355	3	1		3
4435	100	20		1
4455	200	30		2

Chromium.

	%	Intensity.		
W. L.	A.	S.	C.	Av.
2672	3	8		1
2677	4	20		1
2688	2	10		2
2704	1	6		1
2727	1	5		0
2749	3	8		1
2751	3	10		1
2752	3	10		1
2763	3	10		1
2767	4	15		3
2792		10		1
2801	1	10		1
2812	1	10		1
2818	1	8		0
2822	1	10		2
2831	1	20		1
2836	4	30		3
2843	4	15		2
2850	4	10		2
2851	1	7		1
2856	3	10		1
2863	3	10		1
2876	2	5		3

Chromium.

	Intensity.			
W. L.	A.	S.	C.	AV.
2899	1	5		2
2922	1	3		1
2927		5		2
2935	1	4		1
2947	1	3		0
2954	1	4		0
2972	2	10		2
2980	2	10		2
2985	2	10		1
2989	1	10		1
3016	2	3		1
3027		8		1
3041	4	10		2
3050	1	10		2
3119	3	10		1
3120	3	15		2
3125	3	20		3
3132	4	20		4
3147	2	5		0
3368	3	20		1+
3403	3	15		1-

Chromium.

W. L.	Intensity.			
	A.	S.	C.	Av.
3409	1	20		1
3579	30	20		2
3594	30	20		2
3605	30	20		2
3964	6	8		1
3970	5	8		1
3977	6	8		1
3984	4	5		1
3993	3	3		0
4254	50	50		4
4275	50	30	1	3
4290	30	30	1	3
4337	10	8		1
4345	10	10		1
4352	15	10	1	2

Manganese.

	Intensity.			
W. L.	A.	S.	C.	Av.
2576	4	30		5
2594	4	15		4
2606	4	10		4
2610	1	8		1
2618	2	8		2
2626	2	7		2
2633	1	7		2
2638	1	5		2
2640	1	5		1
2656	1	4		0
2667		4		1
2702	1	5		2
2706	1	8		2
2709		4		1
2712	1	5		2
2719		3		1
2795	50	4		2
2805	1	5		1
2813	1	3		0
2815	1	3		1
2831	2	3		0
2870	1	4		1

Manganese

W. L.	Intensity. A.	S.	C.	Av.
2880	1	5		1
2890	1	10		2
2892	1	4		0
2898	1	3		0
2900	1	3		0
2933	3	15		3
2939	3	20		4
2949	3	30		5
3442	2	30		3
3460	2	20		2
3474	1	15		2
3483	2	12		1
3489	2	10		0
3807	1	8		1
3824	4	6		1
3834	8	7		1
4030	100	20		5
4033	100	20		4
4034	50	10		3
4041	20	10		4
4048	8	7		1
4055	4	8		1

Manganese.

	Intensity.			
W. L.	A.	S.	C.	Av.
4064	5	6		1
4070	4	3		1+
4235	10	20		1+
4451	5	10		1+

Titanium.

	Intensity.			
W. L.	A.	S.	C.	Av.
3168	5	15		0
3191	4	10		0
3202	3	10		0
3234	8	15		2
3236	5	6		2
3239	4	6		2
3242	4	10		1
3249	4	10		1
3262	4	15		1
3323	5	10		2
3329	6	10		1
3332	3	8		1
3335	5	10		1
3342	4	10		2
3349	8	10		4
3362	1	30		3
3373	4	20		3
3384	3	20		3
3505	3	30		3
3511	3	30		3
3520	2	8		1
3536	2	15		1

Titanium.

W. L.	A.	S.	C.	Av.
	Intensity.			
3625	2	8		1
3641	15	10		1
3660	3	10		1
3662	2	10		1
3685	8	100		5
3706	2	8		1
3742	3	10		3
3759	10	20		6
3761	10	10		5
3900	5	50		5
3914	5	20		3
4164	2	20		2
4172	1	15		2
4274	15	4		1
4290	10	10		2
4294	10	10		1
4300	15	8		3
4306	20	8		1
4308	4	8		1
4313	2	8	1	1
4315	5	5		1
4338	2	10		2
4358				3
4395	10	20		3

Titanium.

	Intensity.			
W. L.	A.	S.	C.	Av.
4418	2	6	1	1
4444	4	15	2	2
4468	4	15	5	2
4488	1	6		1
4501	4	15	6	2
4550	4	20	8	4
4564	3	10	5	2
4572	3	20	4	3

Iron.

	Intensity.			
W. L.	A.	S.	C.	Av.
3735	50	10		1
3749	30	10		3
3758	30	8		1
3763	20	6		1
3816	20	10		0
3820	50	10		1
3826	30	8		1
3841	15	5		1
3860	30	6		1
3878	15	5		0
3886	20	5		1
3928	15	4		0
3969	15	5	1	0
4005	15	6		0
4045	50	15	2	4
4063	30	10		2
4071	20	8		2
4144	15	5		0
4202	10	6		0
4250	15	6		0

Iron.

W. L.	Intensity. A.	S.	C.	Av.
4260	20	10	1	0
4271	30	10		3
4305	30	15		3
4325	30	15		4
4355		20		2
4383	100	20	1	6
4404	50	15	1	3
4415	20	10	1	1

A comparison of these lists with those of Exner and Haschek will show that some strong spark lines are wanting on every plate and many of the strong arc lines. With regard to the Mg. group at 5183, it should be said that the small intensity given these is due to their being far in the green where the plates were less sensitive. To the eye they appeared as strong as the line at 4481. It will

be seen also that the Mg. lines are much longer on the plate than those of any other substance. This is to be expected, as I have said before that the arc was surrounded by a much brighter halo with this metal than with any of the others. The strong Hg. line at 4358 showed as a long line on every plate, the extensions above and below the arc being almost as bright as the central portion.

Summary.

The results of the foregoing experiments may be briefly summed up as follows.

If, at very low pressures, the discharge is caused to pass across a narrow gap, the cathode particles are shot off only by the near surface of the negative electrode and almost all of them strike against the opposite face of the anode.

The principal action of a magnetic field on the discharge is to increase the potential difference in the gap and consequently the kinetic energy of the cathode rays.

The luminosity of the anode is due to the violent impact of these cathode particles and the spectrum of the light emitted is not analogous to that of either the spark or the

arc. The fact that the spectrum is characteristic of the anode and that the cathode makes no impression seems to merit special attention.

In conclusion I wish to state that this research was carried on under the direction of Professor Ames. My best thanks are due to him for much valuable advice and criticism and for the facilities placed at my disposal, and also to Professor Wood for many suggestions. The kindness and interest of student friends has been in many ways helpful.

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June, 1905.

BIOGRAPHICAL SKETCH.

Robert Edward Loving was born near Wilmington, Virginia, April 20, 1874. His early training was received from an older brother, his sisters' governess, and the neighborhood high school. In October 1891 he left home and farm life to enter Glade Spring Military Academy, and in June 1892 he received the first prize, a scholarship to Richmond College. He was graduated M.A. from this institution in 1898, having been for his last two sessions Assistant in Mathematics and Latin. In the autumn of the same year he entered Johns Hopkins University as a Graduate Student in the departments of Physics, Mathematics, and Astronomy. After remaining there three years he was awarded a fellowship in Physics. He was for the next two sessions Principal of Churchland Academy, Virginia, returning to Johns Hopkins in September 1903. During his stay in this University he followed courses under Professors Rowland, Ames, Wood, Bliss and Whitehead in Physics, Professors Cohen and Hulburt in Mathematics, and Professor Poor in Astronomy. He held appointments in the University as Virginia Scholar 1898-1901 and 1903-4, Fellow in Physics 1901-2 (did not enter on Fellowship) and Lecture Assistant to Professor Ames 1904-5.